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SNOW ALBEDO MODIFICATION
A REVIEW OF LITERATURE

Charles W. Slaughter

October 1969

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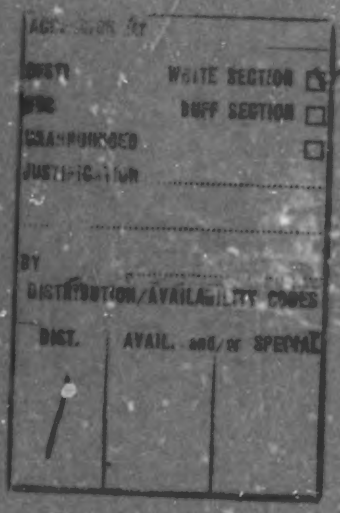

PREFACE

This report was prepared by Dr. C.W. Slaughter, Research Hydrologist, of the Earth Sciences Branch (Dr. D.M. Anderson, Chief), Research Division (Dr. K.F. Sterrett, Chief), U.S. Army Cold Regions Research and Engineering Laboratory. The report has been technically reviewed by Dr. Y.C. Yen, Mr. H. O'Brien and Dr. M. Kumai of the Research Division, USA CRREL.

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SYMBOLS

S	Direct beam solar radiation
h	Angle of sun above the horizon
$S \sin h$	Vertical component of solar radiation
D	Diffuse sky radiation
R	Radiation reflected by snow
G	Atmospheric radiation
E	Radiation emitted from snow cover
L	Sensible heat exchange between air and snow cover
V	Latent heat exchange between air and snow cover
I	Incident radiation
A	Absorbed radiation
B	Transmitted radiation
I_λ	Intensity of radiation in the z direction for the spectral interval $[\lambda$ to $(\lambda + d\lambda)]$ at z units below the surface
I_{λ_0}	Intensity of non-reflected radiation for the spectral interval $[\lambda$ to $(\lambda + d\lambda)]$ at $z = 0$
z	Vertical distance below snow surface
λ	Radiation wavelength, microns
k	Absorption coefficient, cm^{-1}
a	Albedo, normally for visible or short-wave radiation
r	Reflecting power, specified for a defined sector of the electromagnetic spectrum
W	Density of dust application, g/cm^2
A_d	Average actual area covered by dust per unit area of surface
N	Average number of dust particles for a given application density, W
p	Average particle density
d	Average particle diameter
C	Centigrade or Celsius
F	Fahrenheit

SNOW ALBEDO MODIFICATION
A Review of Literature

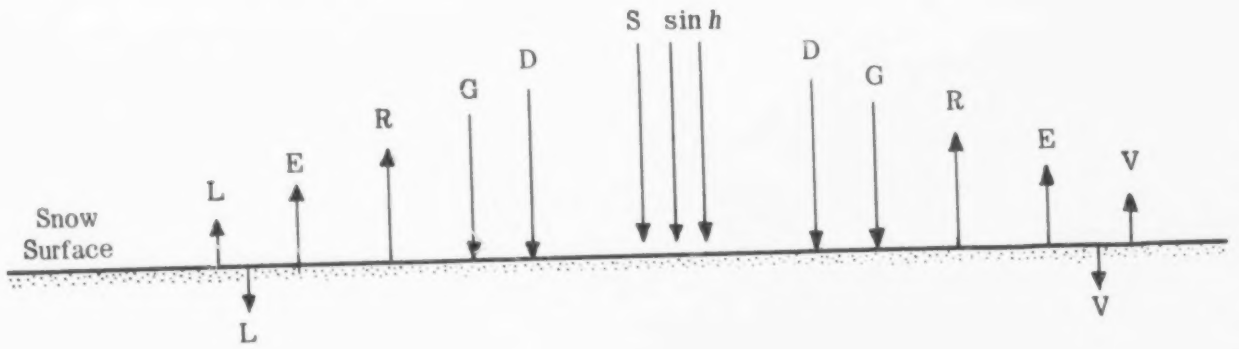
by
Charles W. Slaughter

INTRODUCTION

One of the most striking features of a snow cover is its "whiteness" relative to other naturally occurring materials. This "whiteness" indicates the normally high albedo (the ratio of reflected radiation to incident radiation at a surface) of snow. It is a property that can be altered rather easily and would probably provide an approach to control and management of snow.

ENERGY CONSIDERATIONS

Discussion of albedo modification is best commenced with a consideration of the energy exchange at the surface of the snowpack. The various factors of the heat flux at the surface of a level layer of snow are depicted in Figure 1.



S = Direct beam solar radiation
h = Angle of sun above the horizon
$S \sin h$ = Vertical component of solar radiation
D = Diffuse sky radiation
R = Radiation reflected by snow
G = Atmospheric radiation
E = Radiation emitted from snow
L = Sensible heat exchange between air and snow cover through direct thermal conduction, vertical air mass exchange, and advection
V = Cooling or warming of snow surface through evaporation or condensation (latent heat exchange)

Figure 1. Energy flux at a level snow surface (after Hoeck, 1952).

Modification of $S \sin h$, the direct beam solar energy, and of D, diffuse sky radiation, is possible by various shading techniques, but will not be considered in this paper. Atmospheric radiation (G), sensible heat exchange (L), and emitted radiation (E) are not readily susceptible to manipulation. Control of latent heat exchange (V) is considered elsewhere (Slaughter, 1966). R, radiation reflected by the snow surface, is left as one aspect of this complex which may be modified.

The disposition of radiation incident to a surface may be expressed by the equation (Mantis, 1951)

$$I = R + A + B$$

where I = Incident radiation
R = Reflected radiation
A = Absorbed radiation
B = Transmitted radiation.

For a deep snow cover, $B = 0$, and may be neglected (Mantis, 1951).

In determining energy available for snowmelt, A is the vital factor but it is difficult to measure directly. Therefore, normally I and R are measured and A is determined as residual, assuming $B = 0$.

Absorption of radiation by a homogeneous body follows the Bouguer-Lambert Law (Mantis, 1951, Reifsnyder and Lull, 1965)

$$I_\lambda = I_{\lambda_0} e^{-kz}$$

where I_λ = Intensity of radiation in the z direction for the spectral region [λ to ($\lambda + d\lambda$)], at the point z below the surface
I_{λ_0} = Intensity of non-reflected radiation in the interval [λ to ($\lambda + d\lambda$)] at $z = 0$
k = Absorption coefficient
λ = Radiation wavelength
z = Vertical distance below surface.

The exponent k varies with wavelength, so the Bouguer-Lambert Law holds strictly only for narrow wavelength bands.

A snowpack is generally considered to approximate a homogeneous body (Mellor, 1964). While a natural snowpack commonly has variations of density and grain size, this has not been considered a serious difficulty in energy budget calculations.

The reflecting "power" of a surface is commonly expressed as albedo, a, defined by the equation $a = R/I$. Thus for a thick snow layer with $B = 0$, absorption = $A = I(1 - a)$. The additional effect of internal reflection within the snowpack is not here differentiated from surface reflectivity alone; the difference between the two cases is less than 1% (Giddings and LaChapelle, 1961).

Reflectance varies with wavelength of incident radiation and with angle of incidence of incoming radiation (Mantis, 1951). Reflectance, r, should be stipulated for a definite wavelength, as

$$r = \frac{\text{reflected energy in range [}\lambda \text{ to } (\lambda + d\lambda)\text{]}}{\text{incident energy in range [}\lambda \text{ to } (\lambda + d\lambda)\text{]}}$$

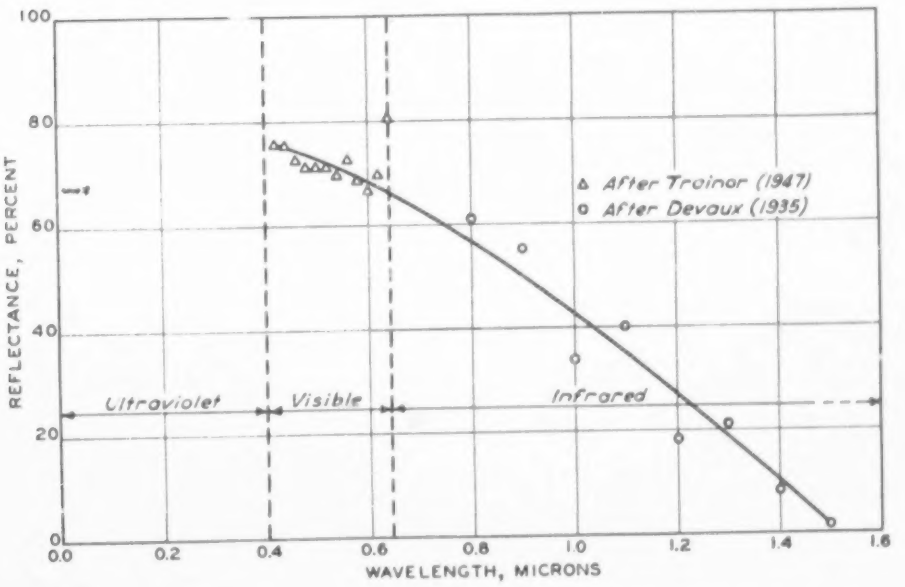


Figure 2. Approximate reflectance of melting snow (from U.S. Arr Corps of Engineers, North Pacific Division, 1956).

So, with albedo = a,

$$a = \frac{\int_0^{\infty} r\, I_\lambda \, d\lambda}{\int_0^{\infty} I_\lambda \, d\lambda}.$$

If r were constant for all wavelengths, a would equal r. Actually, most albedo measurements represent an average value over all wavelengths within the limits of the instrument being used.

It is frequently assumed that radiation reflected from snow follows Lambert's Cosine Law, which indicates that "the intensity of reflected radiation is proportional to the cosine of the angle between reflected rays and a normal to the surface, and is independent of the direction of the incident radiation" (Mantis, 1951; U.S. Army Corps of Engineers, North Pacific Division, 1956). This may be assumed true for fresh snow; however, for surfaces other than fresh, specular reflection is more probably the case. Use of a mean daily albedo figure may compensate for diurnal changes in snow condition and sun angle (U.S. Army Corps of Engineers, North Pacific Division, 1956). If conditions of specular reflection obtain, it would be necessary to take a series of readings over the entire hemisphere above the surface to obtain true values of a or r. This is not commonly done; therefore, most recorded values of albedo and reflecting power are at some undetermined variance from true values (Mantis, 1951).

Approximate spectral reflectance of melting snow is given in Figure 2. This approximate curve is in general agreement with the data of Holmgren (1963), cited by Mellor (1964). For comparison, Figure 3 shows spectral distribution of solar radiation at the top of the earth's atmosphere and at the earth's surface. Apparently melting snow largely absorbs radiation of wavelengths greater than 1.5 μ (see Mellor, 1964). However, Figure 3 shows that little energy reaches the earth in these longer wavelengths.

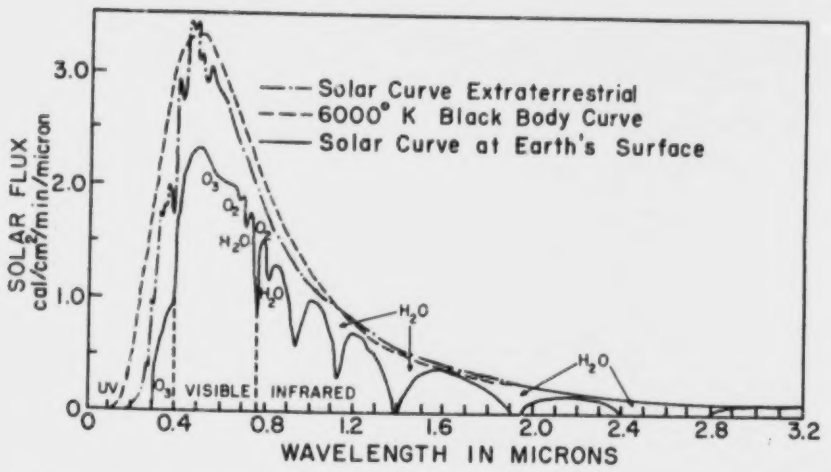


*Figure 3. Extraterrestrial solar flux, solar flux at earth's surface, and flux from 6000K black body (from Gates, 1962).**

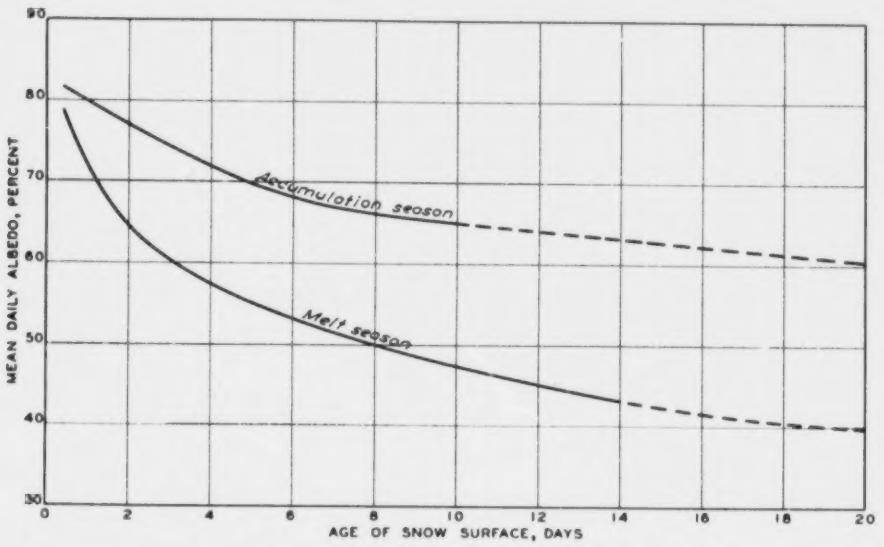


Figure 4. Variation of snow albedo with age (from U.S. Army Corps of Engineers, North Pacific Division, 1956).

Radiation of extremely short wavelengths (ultraviolet, less than 0.36 μ) is shown in Figure 3 to be of small total importance at the earth's surface. As the reflectance of snow for ultraviolet radiation has been estimated at 80 to 85% (Geiger, 1950), this radiation is of little significance in the energy exchange of a snowpack.

The results of several measurements of reflectance r as cited by Mantis (1951) are given in Table I. For comparable wavelengths, reflectance of snow (condition unstated) is approximately 50% greater than that of ice.

Albedo, differentiated from reflectance by not segregating wavelengths, has been determined by numerous workers. Several values for snow cited by Mantis (1951) are given in Table II. For purposes of comparison, albedo values for snow and other natural surfaces as reported by Geiger (1950) are given in Table III. Kasten (1966) reported "visual" albedo of snow in Greenland as 1.0 under both overcast and clear skies. Snow condition was not specified. This is the only report of complete reflection of the visible spectrum noted in this review.

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Table I. Reflectance, r, of snow and ice (Mantis, 1951).

Worker	*Surface*	*Radiation wavelength (μ)*	*Reflectance* Snow	Ice
Hulbert (1928)	Freshly fallen snow	0.3-0.4	35*	
		0.4-0.8	40	
		0.8-2.6	15	
		2.6-7.0	18	
		over 7	26	
Devaux (1935)	Melting snow, large grains	0.6	0.67	
		0.8	0.61	
		0.9	0.55	
		1.0	0.34	
		1.1	0.4	
		1.2	0.18	
		1.3	0.21	
		1.4	0.08	
		1.5	0.01	
Sauberer (1938)	Snow, ice	0.380	0.72	0.44
		0.435	0.74	0.46
		0.475	0.73	0.48
		0.525	0.76	0.50
		0.590	0.76	
		0.596		0.50
		0.630	0.75	0.48
		0.660	0.76	0.50
		0.700	0.75	0.48
		0.735	0.74	0.47
		0.760	0.72	0.43
Suga (1941)	Snow	0.30-0.40	0.9	
		0.40-0.50	1.0	
		0.50-0.75	1.0	
Trainor (1947)	Old snow	0.42	0.757	
		0.44	0.757	
		0.46	0.725	
		0.48	0.712	
		0.50	0.712	
		0.52	0.712	
		0.54	0.698	
		0.56	0.725	
		0.58	0.685	
		0.60	0.670	
		0.62	0.698	
		0.64	0.805	

* Values of Hulbert are merely relative magnitudes, not percent.

Dunkle and Bevans (1956) showed that on theoretical grounds albedo should decrease with increased age of snow. Variation of snow albedo with time is shown in Figure 4. This figure supports data previously enumerated, namely, that a fresh snow surface exhibits the highest albedo.

The penetration of solar radiation into a snowpack was studied by Hand and Lundquist (1942) by placing an Eppley pyrheliometer at various depths in the snow. Some of their results are given in Table IV. They found that "... the amount of transmission varies in proportion to the average quality of snow and is greatly influenced by the factors of snow and intermediate ice layers."

Table V gives comparable figures reported by Kalitin (1939), cited by Rikhter (1945), and reported by Mantis (1951). The instrument used in this work was not specified.

Table II. Albedo of snow surfaces (Mantis, 1951).

Worker	*Snow condition*	*Albedo (%)*	*Instrument and wavelength*
Nutting, Jones, and Elliott (1914)	Fine, dry, drifted	84.7	Photometer – wavelength not stated
	Natural surface, fresh	70.2	
	Old, beady	67.8	
Olsson (1936)	New snow, clear sky	81	Pyrometer – 0.3 μ to 3-4 μ
	New snow, cloudy sky	75	
	Frozen snow, clear sky	75	
	Frozen snow, cloudy sky	65	
	Melted snow, clear sky	59	
	Melted snow, cloudy sky	65	
Morikofer (1939)	New snow	80-90	Not stated
	Settled dry snow	60-80	
	Melting snow	down to 50	

Table III. Albedo of various surfaces for visible portion of spectrum (Geiger, 1950).*†

Surface	*Albedo (%)*
Fresh snow cover	80-85
Cloud surface	60-90
Older snow cover	42-70
Fields, meadows, tilled soil	5-10
Heath and sand	10-25
Forest	5-18
Surface of the sea	8-10

* Instrument used not specified

Table IV. Solar radiation transmitted by a snow cover (Hand and Lundquist, 1942).

Snow depth (in.)	*Incident radiation transmitted (%)*	*Comments*
10	0	Fine granular snow: $\frac{1}{8}$-in. ice layer at a depth of 1¼ in.
2½	1.0	
1	7.8	
7	0	Uniform, fine granular compact snow, average density (% of water on a given volume) 45%. No ice or slush layer.
5¼	1.2	
4	1.8	
$2\frac{1}{8}$	7.8	
1	16.9	
½	22.3	

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Table V. Radiation transmitted by a natural snow cover (Kalitin, 1939).

Snow depth (cm)	*Incident radiation transmitted, neglecting reflection (%)*	*Incident light transmitted, neglecting reflection (%)*
0	100	100
3	90	
5		45
10	20	12
15	5.5; 5.7	3.5
20	3.2	0.34
25	2.3	0.09
30	1.7	0.03
35	1.5	0.005
40	1.2	
45	1.0	
60	0.7	

These data are pertinent when considering the case of fresh snow above a darkened snow or ice surface. They indicate that more than 20 cm of fresh snow would be quite effective in nullifying a darkening treatment.

NATURAL DARKENING OF SNOW AND ICE

Natural dark layers on snow or ice are commonly observed. Dust mixed with falling snow in the spring of 1913 was credited with advancing spring snowmelt nearly a month ahead of "normal" at Wagon Wheel Gap, Colorado (Jones, 1913). A major "dust fall" was reported in the Swiss Alps during a foehn in March, 1947 (deQuervain, 1947). To this dust, which accumulated at the rate of 3 g/m^2, were attributed a 20% increase in absorption of solar radiation in May and consequent disappearance of the snow cover 1¼ months earlier than normal.

Impurities and debris are common on glaciers. Ice "richly sprinkled with yellow dust" has been observed in Greenland (Ahlmann, 1942). On Ellesmere Island, dust and rock particles with mean diameter of about 0.5 mm were deposited on the surface of Gilman Glacier by a blizzard in the spring of 1960 (Hattersley-Smith, 1961).

Parts of the Froya Glacier, in Greenland, were reported to be "sprinkled with small stones and mud," giving rise to a "considerable difference in ablation on clean snow and dirty ice" (Ahlmann, 1942). A discoloration of the surface of the Sonnblick Glacier, European Alps, in June of 1960 reduced albedo to 45 to 49%, compared with 56 to 61% "over the light areas" (Dirmhirn, 1960). This discoloration was alleged to result from dust blown from the deserts of North Africa.

A similar dustfall on the glaciers of the Otztal Alps, Austria, attributed to dust from North Africa and Italy, was reported in the summer of 1962 (Glen, 1963).

Such impurities naturally affect ablation rates (Sharp, 1949). In Greenland, white ice was reported to ablate 1.6 m while "dirty ice" ablated 2.7 m, over the period June 15 to August 25, 1955 (Farrand, 1956). Pal'gov (1954) reported that glacier melting in Khazakhstan (USSR) was increased 10 to 20% by dust on the surface. In the Tien Shan mountains (USSR) average melt of

dirt-covered ice was 9% greater than melt of clean ice (Pal'gov, 1948). On glaciers in the upper Vanch River of Russia, a diurnal melt rate of 6.3 to 6.5 cm was reported for dust-covered ice, while there was no visible melt on clean ice (Zabirov, 1952).

At least one researcher has hypothesized that albedo changes due to dust coming from volcanic fallout may have darkened polar ice sheets enough to effect sea-level changes; this may have been a factor in glaciation fluctuations (Bloch, 1964).

Dirt cones are rather common on glaciers, and their development has been well described (Swithinbank, 1950). Thick accumulations of debris protect the underlying ice from melting, while the surrounding, less well protected surface is lowered by ablation; hence the debris accumulations emerge as "cones." Such features have also been described by other workers (Bout, 1958; Krenek, 1958; Lister, 1959).

Ice wells – holes in snow or ice resulting from differential ablation – are not uncommon. Depths of such "wells" to 90 ft have been reported (Science Service, 1938). "Dust basins" caused by accumulations of dark silt have been found as much as 42 in. across and 16 in. deep (Sharp, 1949). "Algal pits" up to 100 cm in diameter and 25 cm deep, stemming from presence of dark brown algae on the surface, have been described in Greenland (Farrand, 1956). "Cryoconite holes" appear to result from similar accumulations of dust and organic material (Charlesworth, 1957).

A detailed analysis of dirt on snow and ice, and its ecological significance, has been made by Wilson (1958).

ARTIFICIAL DARKENING OF SNOW AND ICE

The qualitative effect of darkening snow has been recognized for many years. It is reported that Benjamin Franklin, in 1761, laid squares of cloth of various colors on snow, and, noting that white cloth remained at the surface while black cloth penetrated down into the snow, wrote "May we not learn from hence . . . that Summer Hats for Men or Women, should be White, as repelling that Heat which gives Headaches to many, and to some the fatal Stroke?" (Life, 1960). In 1885 it was suggested that laying brown paper on snow in winter would promote melt, and, "It is sufficient to cover snow with the thinnest layer of coal dust to see even a greater effect of the same kind" (Woeikoff, 1885).

Savinov (1907) measured the solar radiation absorption of spring snow covered with soot; absorption by soot-covered snow was 0.83 cal/min, while clean snow absorbed 0.34 cal/min.

It has been calculated that in the central Rocky Mountains, snowmelt in summer could be increased by as much as 35 to 45%, assuming an albedo reduction from 0.5 to 0.1 (Martinelli, 1960). A Japanese study showed that in the case of soil scattered on snow, 90% of the heat absorbed by the soil particles was transferred to the snow (Yosida, 1948). Black-painted zinc plates, 0.5 mm thick by 8 cm in diameter, were found to have markedly greater "snow melting power" than had coal particles applied to snow (Yosida and Kozima, 1950).

Hand and Lundquist (1942) applied paint pigments to snow at rates of 1 oz per circular plot 18 in. in diameter; lampblack, chrome green, and ultramarine blue were all effective in promoting radiation absorption, with lampblack the most effective.

A study of seven types of materials on snow, sea ice, and lake ice was undertaken by Arnold (1960) at Isachsen, Northwest Territories, Canada. Materials used were: coarse cinders (2 to 10 mm particles); fine cinders (0.2 to 2.0 mm particles); fly ash (particles less than 0.2 mm); coarse cinders with 75% rock salt added; coarse cinders with 25% rock salt added; fine cinders with 25% rock salt added; and fly ash with 25% fine sand added. Each material was applied to a 1-m^2 plot at each location (snow, sea ice, lake ice). Concentrations used were 100, 300, 500, 700, and 1000 g/m^2. Ablation measurements were made throughout the summer of 1959 by means of leveling from reference stakes to an accuracy of ½ cm.

On both sea ice and lake ice, the 1000 g/m² concentration of fine cinders was most effective, increasing total ablation by about five times over control plots.

Arnold (1961) reported:

> "Larger amounts of the various types of coarse cinder uniformly resulted in an increased loss of snow. When coarse cinder was used without salt, this increase began to decline with amounts greater than 500 gm/sq m. Coarse cinder with 75 per cent salt added acted rapidly, but its final effectiveness was about 20 per cent less than coarse cinder alone. The darkening of the snow surface was perceptible less than with the other materials. Coarse cinder with 25 per cent salt gave results that were very closely related to the degree of concentration of the material. The 1000-gm concentration was little more effective than coarse cinder alone, and the smaller concentrations were less effective. The value of an added amount of rock salt appears small, if a continuing solar radiation absorption effect from a single application is desired. Even at the end of the first day, the coarse cinder with 75 per cent salt had been almost overtaken by plain coarse cinder.
>
> "Fine cinder was the most effective, by a small margin, of all seven materials at the end of the experiment. An addition of 25 per cent salt again produced an initial advantage of about 25 per cent on the first day. This became a 15 per cent disadvantage by the end of the experiment. Increased concentrations of both types of fine cinder generally gave increased effectiveness, but this was not as well marked as with coarse cinder.
>
> "Fly ash, and fly ash mixed with 25 per cent fine sand, were very similar in effectiveness. The unevenness of the snow in the two finest concentrations of fly ash mixed with fine sand made these measurements less reliable. The greatest standard error in these squares was 3.5 cm. The differences between the 100- and 1000-gm concentrations are much less than for the other materials. Both types of fly ash were markedly more effective than fine and coarse cinder in equal 100-gm concentrations, and retained this advantage up to the 700-gm concentrations. The 1000-gm concentrations were only a little less effective than the same amount of fine cinder."*

In 1953 Skorik (1960) studied the effects of various surface additives on ice melt in Dickson Bay, USSR. Preliminary tests at Lake Ladoga, USSR, had indicated that dusting an ice cover with Prussian blue at 0.5 g/m² was more effective in promoting thawing than dusting with "natural" sand at 400 g/m². Dusting with natural sand also led to melting chiefly from the surface, while the Prussian blue penetrated more deeply into the ice, thereby weakening it more severely.

For the Dickson Bay trials, the following substances were used: aniline black, Prussian blue, sand dyed with aniline black and with Prussian blue, natural sand, Cambrian clay, Dickson clay, coal dust, cinders, magnesium powder, aluminum power, Dutch lampblack, calcium chloride, and calcium orthophosphate. The experimental layout and treatment rates are given in Table VI. Each treatment plot was 5 m by 5 m, or 25 m² in area: each treatment was performed simultaneously on two plots. Treatments were applied 2 June 1953.

Particle size distribution of some of the treatment materials is given in Tables VII and VIII.

From the results of this trial, given in Table IX, the most significant conclusions would seem to be, first, "The rate of thawing and destruction of the ice cover depends on the nature and degree of subdivision of the dispersed material as well as on the density of dusting of the ice surface...", and accordingly, "Since the radiation absorptivity of hard, opaque subdivided materials depends on their degree of subdivision as much as on their colour, in order to promote the

---

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Table VI. Location of experimental areas in Dickson Bay (Skorik, 1960).

5		4	
10	9		8
15		14	
20	19		18
25		24	
30	29		28
35		34	
40	39		38
45		44	
50	49		48
55		54	
60	59		58
3	2		1
7		6	
13	12		11
17		16	
23	22		21
27		26	
33	32		31
37		36	
43	42		41
47		46	
53	52		51
57		56	

1. Sand, 400 g/m^2
2. Sand, 400 g/m^2 plus Prussian blue, 0.5 g/m^2
3. Sand, 400 g/m^2 plus Prussian blue, 1.0 g/m^2
4. Prussian blue, 0.5 g/m^2
5. Prussian blue, 1.0 g/m^2
6. Prussian blue, 1.0 g/m^2
7. Prussian blue, 0.5 g/m^2
8. Sand, 400 g/m^2 plus Prussian blue, 0.5 g/m^2
9. Sand, 400 g/m^2 plus Prussian blue, 0.5 g/m^2
10. Sand, 400 g/m^2
11. Aniline black, 2 g/m^2
12. Aniline black, 1.0 g/m^2
13. Sand, 400 g/m^2 plus aniline black, 2 g/m^2
14. Sand, 400 g/m^2 plus aniline black, 1.0 g/m^2
15. Coal dust, 5 g/m^2
16. Coal dust, 5 g/m^2
17. Sand, 400 g/m^2 plus aniline black, 1.0 g/m^2
18. Sand, 400 g/m^2 plus aniline black, 2 g/m^2
19. Aniline black, 1.0 g/m^2
20. Aniline black, 2 g/m^2
21. Calcium chloride, 40 g/m^2
22. Cinders, 100 g/m^2
23. Cambrian clay, 20 g/m^2
24. Cambrian clay, 10 g/m^2
25. Cambrian clay, 2 g/m^2
26. Cambrian clay, 2 g/m^2
27. Cambrian clay, 10 g/m^2
28. Cambrian clay, 20 g/m^2
29. Cinders, 100 g/m^2
30. Calcium chloride, 40 g/m^2
31. Coal dust, 10 g/m^2
32. Coal dust, 20 g/m^2
33. Dickson clay, 20 g/m^2
34. Dickson clay, 10 g/m^2
35. Dickson clay, 2 g/m^2
36. Dickson clay, 2 g/m^2
37. Dickson clay, 10 g/m^2
38. Dickson clay, 20 g/m^2
39. Coal dust, 20 g/m^2
40. Coal dust, 10 g/m^2
41. Coal dust, 1.0 g/m^2
42. Aluminum powder, 6 g/m^2
43. Aluminum powder, 1.0 g/m^2
44. Magnesium powder, 6 g/m^2
45. Magnesium powder, 1.0 g/m^2
46. Magnesium powder, 1.0 g/m^2
47. Magnesium powder, 6 g/m^2
48. Aluminum powder, 1.0 g/m^2
49. Aluminum powder, 6 g/m^2
50. Coal dust, 1.0 g/m^2
51. Dutch lampblack, 1.0 g/m^2
52. Dutch lampblack, 0.5 g/m^2
53. Calcium orthophosphate, 0.5 g/m^2
54. Coal dust, 0.5 g/m^2
55. Coal dust, 2 g/m^2
56. Dutch lampblack, 1.0 g/m^2
57. Dutch lampblack, 0.5 g/m^2
58. Calcium orthophosphate, 0.5 g/m^2
59. Coal dust, 5 g/m^2
60. Coal dust, 2 g/m^2

Table VII. Grain size composition of several dispersible substances used at Dickson Bay, as determined by the method of Klenova and Avilov* (Skorik, 1960).

Dispersible substance	*% Composition*				
	1.0 mm	*1.0-0.1 mm*	*0.1-0.05 mm*	*0.05-0.01 mm*	*0.01 mm*
Sand from Dickson Island		94.1	5.69		
Cambrian clay				10.22- 9.1	89.42-90.18
Dickson clay	1.1-3.2	6.5- 6.1	35.6 -35.9	41.1 -41.9	16.8 - 16.1
Coal dust (Noril'sk coal)		48.6-49.9	25.9 -25.9	11.4 - 11.9	14.1 - 12.3
Coal ashes (Noril'sk coal)	2.7-3.9	2.9- 2.4	20.1 - 19.2	24.9 -22.3	52.1 -56.1

* The method of Klenova and Avilov is not given, nor is the reference cited by Skorik.

Table VIII. Grain size composition of several dispersible substances used at Dickson Bay, according to sieve analysis data (Skorik, 1960).

Dispersible substance	*% Composition*					
	2.0 mm	*2.0-1.0 mm*	*1.0-0.5 mm*	*0.5-0.25 mm*	*0.25-0.10 mm*	*0.10 mm*
Coal cinders (Noril'sk coal)	25.56	13.19	11.37	8.16	4.86	35.18
Coal dust			10.54	4.37	45.04	38.56
Sand			0.9	0.8	92.4	5.69

Table IX. Relative thawing of dyed and dusted ice areas at Dickson Bay, for 9 and 23 June 1953 (Skorik, 1960).

Dye or dust used	*Experimental area no.*	*Thawing of ice (cm)*	
		9 June	*23 June*
Natural sand, 400 g/m^2	1, 10	10	40
Prussian blue, 0.5 g/m^2	4, 7	28	50
Prussian blue, 1.0 g/m^2	5, 6	30	60
Sand, 400 g/m^2 plus Prussian blue, 0.5 g/m^2	2, 9	25	30
Sand, 400 g/m^2 plus Prussian blue, 1.0 g/m^2	3, 8	28	45
Aniline black, 1 g/m^2	12, 19	20	32
Aniline black, 2 g/m^2	11, 20	25	34
Sand, 400 g/m^2 plus aniline black, 1 g/m^2	14, 17	22	50
Sand, 400 g/m^2 plus aniline black, 2 g/m^2	13, 18	22	55
Coal cinders (from Noril'sk coal), 100 g/m^2	22, 29	22	54
Coal dust, 20 g/m^2	32, 39	15	60
Coal dust, 10 g/m^2	31, 40	15	54
Coal dust, 5 g/m^2	15, 16	15	23
Coal dust, 2 g/m^2	55, 60	0	
Coal dust, 1 g/m^2	41, 50	0	15
Cambrian clay, 20 g/m^2	23, 28	20	25
Cambrian clay, 10 g/m^2	24, 27	10	18
Cambrian clay, 2 g/m^2	25, 26	0	0
Dickson clay, 20 g/m^2	33, 38	15	15
Dickson clay, 10 g/m^2	34, 37	10	10
Dickson clay, 2 g/m^2	35, 36	0	0
Bare ice surface	0	7	20

destruction of ice it is more practical to use small quantities (several grams per square metre) of highly dispersible substances rather than large quantities of substances with low dispersity, e.g. sand" (Skorik, 1960). The latter concept was also recognized by Arnold (1960).

A more recent Canadian study has largely substantiated these findings (Williams and Gold, 1963). Regarding the effects of particle size on blackening, they wrote:

> "The decrease in albedo obtained by dusting will depend on the amount of the surface that is covered by the dust. Let the density of application be W gm/cm^2, the average diameter of the particles d cm and the average density of each particle p gm/cc. Assuming that the particles are spherical, the average weight of a particle is $p\pi d^3/6$. For a density of application W, the average number of particles will be $N = 6W/p\pi d^3$.
>
> "The average maximum cross-sectional area of a particle is $\pi d^2/4$.
>
> "The average actual area covered by the dust per unit area of surface is $A_d = (\pi d^2/4)N = (3/2)(W/pd)$.
>
> "If W, p and d are expressed in the same system of units, A_d is a dimensionless number whose value is independent of the . . . units used. From the expression for A_d, it is seen that the coverage obtained for a given density of application [W] is proportional to the density of application [number of particles per unit area, N] and inversely proportional to the average diameter and density of the particles."

Tests made with Ottawa Valley crushed limestone showed that albedo changed nearly linearly with A_d, down to the albedo of the limestone dust. In this case, $A_d = 0.21$ with $d = 1.2$ mm, $p = 2.4$ g/cm^3, and $W = 1150$ tons/mile^2. Correspondingly, $A_d = 0.21$ with $d = 0.5$ and $W = 475$ tons/mile^2; decreasing particle size to $d = 0.1$ mm would cut the required application to 95 tons/mile^2, A_d remaining equal to 0.21. This example readily illustrates how a decrease in particle size can cut the weight of a given material needed to obtain a specified albedo change.

Williams and Gold also noted that for a given particle size, weight per unit volume varies directly with particle density. Assuming a particle density for heavy materials such as crushed rock or sand of 2.4 to 3.0 g/cm^3, and a particle density of 0.5 for soot, it would take about $\frac{1}{5}$ as much soot to produce the same albedo reduction as created by crushed limestone of the same particle size (ignoring color differences between soot and sand).

From their field experiences, Williams and Gold (1963) indicate that the "practical range" of average particle size of dusts is probably 0.1 to 2.5 mm, and the minimum albedo attainable is about 20%.

Through a consideration of the energy balance at a snow surface, the same workers have shown that dusting of snow will be most effective when the normal surface albedo is high, so that net short-wave radiation (radiation absorbed) can be significantly increased by decreasing the amount reflected. They also note that heat loss by convection from the surface and by evaporation may in some cases balance the increase of energy absorbed due to darkening, thus placing a natural limit, varying with local conditions, on the effectiveness of albedo reduction. (Emission of long-wave radiation, which varies according to the fourth power of the absolute temperature of the surface, as described by the Stefan-Boltzmann Law (Reifsnyder and Lull, 1965), will not be affected by albedo change if the snow is melting as the surface temperature will remain at 0C.) They further estimate, from consideration of the normal solar radiation available, that, "In the southern latitudes [of Canada] melting will probably not occur if the average air temperature is below 20 to 25F. In northern latitudes, the critical temperature will probably be about 5F lower because of the increased short-wave radiation available in the breakup period" (Williams and Gold, (1963).

In a subsequent report, Williams (1967) discussed ice dusting tests conducted during 1964 and 1965 at Ottawa, Inuvik (N.W.T.), and Baffin Island. Treatments employed included simply removing the overlying snow cover from lake ice, or covering it with finely crushed rock, mud pumped from a lake bottom, sand, and colloidal graphite and carbon powders sprayed in water suspension.

Powdered materials sprayed onto ice in suspension were not so effective in promoting melt as dry solids (crushed rock, sand), but were more effective than was simply removing the snow cover from an ice surface. Williams concluded that "Dusting... is not very effective if the minimum daily air temperature falls much below 32F. This... applies to all latitudes."

Bonin and Teichmann (1949), in a report prepared under contract for the U.S. Coast Guard, have given the following criteria for selection of albedo-modifying materials:

Physical Properties

1. absorptivity
2. conductivity
3. density
4. state of aggregation
5. particle size, if a solid
6. viscosity, if a liquid
7. freezing point, if a liquid
8. toxicity
9. solubility

Economic Considerations

1. availability
2. cost of material
3. cost of shipping and handling
4. cost of application

They elaborated on these as follows:

"The absorptivity is of importance, since it is a measure of the amount of solar energy that will be captured by the layer and therefore, utilized to melt ice.

"The conductivity of the material must be considered, since this would be a measure of its ability to give up heat to the ice sheet. If the material is immersed in water, the conductivity will play only a minor role.

"The density of the material is important as it will determine if the material will float on the melted ice or remain on top of the ice sheet.

"The state of aggregation is important as far as the method of applying the substance is concerned. A liquid can be applied by spray nozzles, while a solid will require different methods of application.

"The particle size of a solid material will influence the method of application; it should be chosen so that the maximum surface is utilized for the absorption while the surface-over-weight ratio should be such that the action of the wind will be minimized. This will materially aid to maintain a more uniform coverage of the area.

"If a liquid is employed the freezing point should be below that of water and it should have a low viscosity. The lower viscosity will facilitate its application.

"The material chosen should be non-toxic. This is desirable from a standpoint of handling of material and from a water pollution standpoint, which could be detrimental to human and animal life.

"The material should not be soluble in water. This is desirable as it would otherwise require periodic applications.

Table X. Absorptivity of various materials for solar energy (Bonin and Teichmann, 1949).

Material	*Absorptivity*	*Material*	*Absorptivity*
Bricks:		Pigments:	
Gault, cream	0.38	White $PbCO_3$	0.12
Fletton, light portion	.45	White MgO	.14
Light buff	.52	White ThO	.14
Darker buff	.60	White ZrO	.14
Lime clay (French)	.50	White $MgCO_3$	.15
Wine cut, red	.61	White CnO	.15
Stock, light fawn	.64	White ZnO	.18
Fletton, dark portion	.65	White Al_2O_3	.16
Sand lime, red	.72	Yellow $PbCrO_4$	.30
Red	.70	Yellow PbO	.48
Mottled purple	.79	Green Cu_2O_3	.73
Stafford, blue	.90	Red Fe_2O_3	.74
		Blue Co_2O_3	.97
Concrete tiles:		Lampblack paint	.97
Uncolored	0.65		
Brown	.85		
Brown, very rough	.87		
Black	.91		

> "The material chosen should be readily available at low cost close to the point of application. It should be handled without much equipment and should cover the surface uniformly."

They conclude that no one sustance is likely to satisfy all requirements. From economic considerations, industrial waste or by-products would be desirable; for effectiveness, the darker the material and the rougher the surface, the more effective will be the treatment. They list the solar absorptivities of various materials (Table X) and conclude that lampblack is the most desirable from this last viewpoint.

FIELD RESULTS

The effect on ablation of adding stones and pebbles at various rates to a glacial ice surface was studied briefly in Greenland (Kuhlman, 1959; Fristrup, 1960). On clean 50-cm by 50-cm ice surfaces, stones were placed uniformly at rates of 1 g/cm^2, 1.9 g/cm^2, 4.2 g/cm^2, and 8.6 g/cm^2. After 36 hr the relative ablation of these treatments, taking ablation of clean ice as 1.0, was respectively 1.2, 1.35, 0.85, and 0.7: after an additional 18 hr (54 hr total), the corresponding figures were 1.3, 1.6, 0.8, and 0.6.

On a glacier in the Caucasus Mountains an ice surface covered with "fine rubble," particles less than one square decimeter (dm^2), showed a consistently faster melt rate than ice covered with "coarse rubble," particles 5 to 8 dm^2. The latter in turn consistently melted faster than open ice (Valesnik, 1936). In the Tien Shan mountains ice melt has been increased by scattering coal dust on the surface of the Karabatkak Glacier (Mursaev, 1953). Dusting of glacier ice, together with blasting surface ice, has been recommended for increasing flow of glacier-fed streams in such areas (Avsiuk, 1962; Popov, 1936).

Work at the Kamchatka Agricultural Experiment Station, USSR, showed that dusting snow with ashes at a rate of 0.5 to 1.0 ton/hectare, or with soil at five times this rate, shortened the melt period by 12 to 13 days (Titlianov, 1941). Addition of slag and fuchsin to snow in layers 0.2 to 0.5 mm thick reduced albedo to as little as 29%, compared with 84% for untreated snow (Georgievskii, 1939).

Again in the Tien Shan mountains, a thin layer of coal dust, 5 tons/km^2, increased heat absorption in firn three to six times, and in glacial ice up to 1.4 times; melt rates increased correspondingly (Avsiuk, 1953, 1954). Application of coal dust to plots on a Peruvian glacier resulted in lowering the surface of darkened snow 8 in. below an untreated surface within a day after application (Howell, 1953). Blackened snow was reported to have albedo of 20 to 35%, as compared with 73 to 92% for clean, dry snow; 66 to 86% for clean, wet snow; and 58 to 73% for clean, wet, settled snow (Azuma, 1956). Blackening reduced albedo by 20% even under 1 cm of new snow.

On the Wasatch Plateau of Utah daily melt of clean snow averaged 1.2 to 1.3 in. while snow darkened by dust and soot melted at 2.0 to 2.4 in./day (Croft, 1944).

Magono and Kumai (1955) studied the effect of soil on snowmelt. They reported that soil scattered on the snow surface at 2.0 liters/m^2 gave the greatest increase in snowmelt, although 0.1 liter/m^2 was "most suitable" from an economic standpoint.

Shul'ts (1958) found that the effectiveness of all darkening materials tested by him, including coal dust and soot, was short-lived, the effect being lost six or seven days after application. By way of contrast, a Japanese study reported that in scattering ashes or soil on snow, maximum snowmelt was reached about five days after treatment, followed by a gradual decrease in melt (Takahaski, 1946).

Also in Japan, an application of 38.4 qt of black soil to 36 m^2 of snow caused melting of that snow in 10 days as opposed to 18 days for clean snow (Shioda, 1951).

A Russian study in Kuybyshev Province found maximum melting intensity from treatment with 225 kg/hectare of ashes (Savchenko-Bel'skii, 1951b).

At the under-snow camp of the Norwegian-Swedish-British Antarctic Expedition, an unplanned blackening of the overlying snow by the soot of diesel-burning cookstoves was reported to have caused unexpected snowmelt and consequent serious leakage into the base (Giaever, 1955).

AGRICULTURAL APPLICATIONS

Many snow-blackening attempts have been initiated for agricultural improvements. Use of black powder on snow to warm the soil of vegetable gardens was advocated in Russia in 1924 (Trushin, 1957). In Alaska use of coal dust on gardens was found to be useful in freeing fall-tilled soil from snow, thus increasing length of growing season. This technique was also found to result in better root development of cabbage (Bensin, 1952a). The practice was so promising that a bulletin was printed giving methods and techniques for various crops in the Fairbanks area (Bensin, 1952b). Similar practices have been proposed for melting away glaciers to prolong growing seasons and improve local climates (Landsberg, 1940).

Snow blackening has been advocated as a means of favorably affecting the soil moisture regime. According to one study, "One-m. wide strips of dark material (ashes, soil, peat) spread over the snow cover at intervals of 7-10 m. effected earlier and more intensive snowmelting and rapid soil thawing, which produced good water penetration into the soil" (Slobodchikov, 1951). Aerial application of ashes in strips 50 m apart was reported to have caused "better infiltration into the soil," decreasing erosion (Savchenko-Bel'skii, 1951c) and increasing soil moisture at depths of 20 to 25 cm by 8% over untreated fields (Savchenko-Bel'skii, 1951a).

Covering snow with strips of powdered peat markedly accelerated snowmelt and was found effective in "increasing the accumulation of meltwater in the soil" (Kolchin, 1950, 1951). Similar findings by other researchers are reported by Trushin (1957); however, in a case where snow cover was slight, with some ridges of soil exposed above the snow, no favorable effect on soil moisture could be ascertained.

Japanese tests of carbon black to hasten melt from rice fields showed best results with an application rate of 100 kg/hectare applied with a power sprayer (Kojima, 1959, 1961). A similar trial in tree nurseries, using soil on snow, gave a snow cover disappearance 12 to 13 days earlier than controls (Shidei and Kotama, 1951). In an unrelated study, acceleration of planting time by 4 days in forest nurseries of the USSR was reported following application of wood ashes at 300 kg/hectare (Shevchenko, 1953).

A combined application of fertilizer with snowmelt accelerators has been proposed for agricultural areas (Lau, 1940).

Recently a more unusual application has been "...use of coal dust...to hasten melt as a means of controlling snow mold disease of winter wheat" in the state of Washington (*Solar Energy*, 1965).

Increased water supply for irrigation projects has been a goal of some researchers. It was calculated in 1953 that the annual runoff of mountain rivers in the Tien Shan region of Asia might be increased as much as 54% by snow blackening (Avsiuk, 1953). A Chinese test with this objective was made in 1958, with best results obtained using charcoal (Chu, 1959).

One dissenter from this means of improving water supplies is Shul'ts (1963). After preliminary work on melt acceleration in central Asia (Shul'ts, 1958) he assumed the following:

> "...blackening may bring about intensification of melting only in the presence of the direct rays of the sun, during overcast days its action will come to nothing ...the reflective capacity of bare glacial tongues is so low that blackening may produce an entirely insignificant effect...only 50% of the melting of snow is accomplished by the action of direct solar radiation...the blackening quickly disappears...the dusting of various fine powdery materials from an airplane in the mountains is excluded, since it is not possible from an altitude of less than 150 meters."

He concluded that total water release attainable by increasing melt is not enough to make a significant contribution to water needs of central Asia during dry years. However, it has been reported that in Kansai Province, China, 19 million m^3 of water was made available for irrigation by "laying black material on the surface" of snow in the mountains (Hong Kong Correspondent, *The Times*, 1961).

FLOW REGULATION

Snowmelt control for alleviation of flood conditions has been reported in the USSR (Antrushin, 1961): "Distribution of more than 4000 tons of various substances on these rivers – Onega, Northern Dvina, and Neman rivers – averted high floods in Arkhangelsk during the last few years...," by removing much of the ice cover before time of normal spring breakup and thus preventing ice jams. Effective substances used included ashes, foundry loam, dark sand, phosphate fertilizers, dust, and salts such as potassium chlorite.

Use of coal dust to increase meltwater flow to a power station in the Andes in 1934 has been noted (Bloch, 1964). More recently, carbon black has been used to increase flow to reservoirs built for power generation in Japan (Taketa and Murakami, 1956). Treatment was found to be

effective at temperatures below 0C and under as much as 20 cm of new snow. This technique permitted increasing the power production of Muira Dam (Nagano Prefecture) by 300,000 to 380,000 kw-hr in 1958 (Mikami, 1958). Both helicopters and electric blowers (on the ground) were used in application (Kansai Electric Power Co., 1958a, 1958b).

NAVIGATION

Improvement of navigation conditions by accelerating ice breakup has received fairly widespread attention. The previously discussed Armour Research Foundation report was directed primarily to improvement of navigation (Bonin and Teichmann, 1949; Adlam, 1950).

Working on the Irtysh River, USSR, Miasnikov (1959) found that cinders of 1.2- to 1.5-mm diameter, applied at 0.3 to 0.4 kg/m^2, were most effective in melting ice; dusted ice surfaces melted 8 to 10 days earlier than clean ice. He recommended application 30 to 35 days before natural breakup (50 days in Arctic regions) for best results.

Near Archangel, USSR, use of "dark substances" on ice, applied by air at 300 to 500 kg/hectare in mixture with 50 to 100 kg/hectare of salt, was credited with breakup of ice 15 to 20 days earlier than normal (Antrushin, 1956).

Opening of the Northern Dvina River, USSR, for navigation "several days earlier" was a side effect of ice darkening for flood control (Antrushin, 1961).

Aerial dusting of snow and ice with coal dust was credited with opening the Irtysh River, USSR, for navigation up to 20 days early, as well as with protecting hydraulic structures from ice-pressure damage and removing ice from around wintering ships (Konovalov and Miasnikov, 1956). Similar operations on Pevek Bay, in the East Siberian Sea, are reported by Peschanskii (1960). It has also been reported that along the Northern Sea Route, salvaged foundry and diesel-oil wastes are "... the most economical and practical combination of materials tested so far by the Soviets" for ice darkening (U.S. Department of Commerce, 1959).

A rather thorough discussion of this application of albedo modification is given by Laktionoff (1957), who found best results with applications of fine cinders (0.2 to 1.5 mm in diameter) and coal powder (0.2 to 3.0 mm in diameter) at 400 g/m^2, applied 30 to 35 days before the ice generally starts to break up.

OTHER USES

In Norway use of finely ground peat on roads to accelerate spring melt of snowdrifts has been reported (Kruger, 1949). A similar technique has been tested in California (Lang, 1952), where the California Edison Company tried using soot recovered from the stacks of its steam power plants to melt snow from high-elevation roads. Melt rate was increased by 50% with an application of 10 lb/100 ft^2. This success led to use of soot for melt acceleration around high-elevation hydraulic structures, to cut the expense of digging them out in the spring.

In the Antarctic, black powder has been used to outline airfield boundaries and facilitate judging distances while landing. Such lines were found to sink into the snow surface to a depth of 2 ft "not many days" after application (Giaever, 1955).

While there are probably many instances of other uses of snow and ice darkening, the foregoing covers the various applications encountered in this review of the literature pertaining to albedo reduction of snow.

SNOWMELT RETARDATION

Decreasing the melting rate of snow has not received the same attention as increasing it with respect to either research or application. This can be attributed to the relatively high albedo of even old, "dirty" snow fields in comparison with other natural surfaces (Table III), making albedo increase difficult.

It is generally recognized that a sufficiently thick layer of material over a snowpack or ice surface can insulate it and thus delay melt. Ostrem (1959) found that a layer of sand and gravel more than 0.5 cm thick caused a decrease in melt rate of glacier ice. While normal (uncovered) ice ablation was about 4.5 cm/day, melt decreased to 3 cm/day under a 6-cm layer, and to less than 1 cm/day under a 20-cm layer of sand and gravel.

On a glacier in the Tien Shan mountains, "Dirty bare ice melted at a mean rate of 7.9 cm/day; ice under a 10-cm layer of debris at 3.2 cm/day; and melting under 30-50 cm of debris was 1.1 and 0.85 cm/day" (Nozdriukhin and Freifel'd, 1958).

Deposition of 25 to 30 cm of volcanic ash on Mt. Ruahepu, New Zealand, in 1945 was sufficient to protect underlying ice from ablation (Krenek, 1958).

In Colorado preliminary tests indicated that a layer of sawdust 5 to 8 cm thick might reduce the snowmelt rate almost 50% (Martinelli, 1960; Hoover, 1960). In glacial studies, Sharp (1949) has observed that layers of sand 0.5 to 0.75 in. thick are sufficient to insulate ice. He also noted that coarse material must be thicker than fine material to provide equivalent insulation, and that dry sand is a better insulator than moist sand.

Compacted snow is commonly used for roads and runways in northern areas (Kingery, 1963). Use of coverings to protect compacted runways from melt has been proposed. An aqueous foam, sprayed on the snow surface, initially appeared to have good insulation and stability for runway protection (Grove, Grove, and Aidun, 1963). However, later field tests (Stehle, 1964) have shown that cold-weather application is a problem, foams do not hold up well under traffic, and cost, at Pt. Barrow, Alaska, was greater than that of sawdust imported for the same purpose.

Shih (1963) has studied snow compaction for reducing soil erosion by meltwater. He compared water yields from loose (control), compacted, compacted and mulched, and plowed snow. Initially the compacted and mulched snow yielded 0.36 liter/hr of water, the plowed snow 0.13 liter/hr, the control 0.1 liter/hr, and the compacted snow only 0.03 liter/hr. At a later date, when the soil had thawed to a depth of 2.5 cm under the control plot, thaw had reached only 1.5 cm under plowed snow and 0.5 cm under compacted and mulched snow; no thaw had occurred under compacted snow. Compaction was thus shown to be effective in retarding both snowmelt and thaw of underlying soil.

Another Russian worker has proposed snow compaction and mulching with straw and peat in contour strips for control of snowmelt runoff (Presnijakova, 1962). Slobodchikov (1951) advocated snowbanks made by plows and compacted by hand, spaced 15 to 30 m apart, for delay of melt. Such banks "... accumulated up to 85% of the meltwater and prolonged the period of snowmelting for 7 days."

A rather unusual problem found in some mountain areas is control of flash floods from rapid melt of glacier ice (Kavetskii and Vetiutnev, 1959). It has been suggested that control of such rapid melt be achieved by burning large quantities of leaves, peat, straw, or coal to produce heavy smoke over the glacier and reduce the amount of solar radiation reaching the ice surface (Popov, 1936). Successful use of smoke generators for the same purpose has been more recently reported (Kavetskii and Vetiutnev, 1959).

While no literature references to other applications of melt retardation have been noted, it would seem that this practice, if field techniques could be perfected, would have application in many mountain areas in reducing spring peak flows due to snowmelt and in increasing water yield later in the season, thus benefiting agricultural areas dependent on late-season irrigation.

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13. ABSTRACT

A summary of published information on snow albedo modification is presented. Consideration of energy balance parameters is followed by discussion of qualitative and quantitative results of albedo modification, both increasing (lightening) and decreasing (darkening). Practical applications of albedo modification are discussed.

14. KEY WORDS

Albedo
Radiation absorption
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